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On the effect of surface roughness and material on the subcooled flow boiling of water: Experimental study and global correlation

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ABSTRACT

In this paper, a new correlation based on experimental results for subcooled flow boiling of water at low pressure is proposed, preceded by a brief review on how the solid–fluid interaction has been dealt with in past correlations. The experimental sample comprises seven heating surfaces of different material (copper, aluminium and stainless steel) and roughness. The experimental facility is presented in detail and the surface morphology of each test specimen is analysed by means of an optical interferometer. The correlation is based on the assumption that the effect of material and roughness can be captured by means of modifiers of a general expression. The surfaces chosen in this work were selected to capture a broad range of industrial applications, and, though the correlation found fits well in the range of commercial and relatively high values of R_a (up to 7 μm in the case of copper), further study is needed for larger values, as a discontinuity in the effect was observed, which has been previously determined by some authors. Thus, the proposed global correlation permits the calculation of the boiling heat flux taking into account, in addition to the more classical parameters such as pressure and bulk temperature, the effect of both the roughness and material of the wall heater, allowing its general use in low pressure applications such as those commonly found in the automotive industry.

1. Introduction

Heat transfer is still a developing science in many fields of different industries such as nuclear refrigeration, micro-electronic cooling devices or automotive gas recirculation systems. One of the major goals at the current time is to achieve even more compact exchangers to save space and weight. In this context, heat transfer employing boiling mechanisms is a proper option to take into account. Nevertheless, despite being analysed in depth since the first half of the 20th century, nucleate boiling phenomenon is still unresolved at a global scale and no coherent theory has been established [1–6] mainly due to the great complexity of mass and energy transport mechanisms related with the two phases and the wide range of factors involved. This complexity is explained by the variety of characteristic length and time scales that take part in the process of bubble nucleation, growth, detachment, coalescence and collapse.

Probably the main advantage of nucleate boiling is achieving higher heat fluxes with relatively small increments of surface temperature. For example, in most conventional cases of the automotive industry as in EGR coolers or radiators without vapour separators or condensers, this heat transfer mechanism is used within reasonable limits avoiding a net generation of vapour, which may cause problems of vapour agglomeration in recirculating and top zones. In consequence, the heat transfer process must be run under subcooled conditions [7].

There are two main ways of approaching boiling characterisation, experimental studies and different levels of modelling techniques. Frequently, models dealing with nucleate boiling can be divided in two groups. The first group is comprised by mechanistic models that tackle the problem of identifying and modelling the physical parameters taking part in bubble nucleation phenomenon (e.g., bubble creation, growth, and departure diameter, nucleation frequency, nucleation site density and so on). The second type of models are normally called semi-empirical which instead of trying to reproduce the heat transfer at the wall by the individual contribution of the sub-processes involved, they directly relate it with the operational conditions and bulk properties of the materials involved.

As aforementioned and despite the big advances in recent years, no strong theoretical and global mechanistic model has been developed yet [5,6]. As noted by several authors [5,8] due to the vague knowledge of bubble formation at macro and microstructure levels, many of the past and recent predictive methods in practice are based on empirical and semi-empirical models.

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Nomenclature

Bo	boiling number
c	heat capacity [J kg^{-1} K^{-1}]
C'	Mc. Adams constant in Eq. (9)
C_w	Cooper constant in Eq. (1)
E_F	enhanced factor in Eq. (11)
F	VDI model functions in Eqs. (2)–(7)
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
M	molar mass [kg mol^{-1}]
n	exponent in the asymptotic model in Eq. (10)
p	pressure [Pa]
P_f	characteristic boiling parameter of the fluid [K^{-1} μm^{-1}] in Eq. (5)
$p*$	reduced pressure
q''	heat flux [W m^{-2}]
R_a	arithmetic mean roughness height [μm]
$R_{p,old}$	$=R_a/0.4$ (DIN 4762) [μm]
Re	Reynolds number
S	suppression factor in Eqs. (11), (13), (15)
S_a	arithmetic mean surface height [μm]
T	temperature [K]
Abbreviation	
AT	after tests
BT	before tests
CHF	critical heat flux
HTC	heat transfer coefficient
ONB	onset of nucleated boiling
Greek	
δ	thickness [m]
Δ	increment
ρ	density [kg m^{-3}]
ϕ	boiling function in Eq. (12)
Subscripts	
b	bulk
c	critical state
Cu	copper
fc	forced convection
min	minimum
max	maximum
nb	nucleated boiling
r	reduced state
sat	saturated state
sub	subcooled
tp	two phase
w	wall

Recently, the performance of mini and microchannels on boiling behaviour has received greater attention due to the increasing interest in compact heat exchangers employing this type of heat transfer technology. However, there are only a limited number of publications studying flow boiling and CHF from the experimental point of view [9–12]. Recently, Cikim [13] incorporated the effect of surface coatings on the boiling behaviour of this type of system. These works examine the same issues addressed in the present work, but the scales involved in the development of the bubbles compared to the scale of the channel require a specific approach to the process.

This work addresses the experimental characterisation of the subcooled nucleate boiling of water at low pressure as an experimental contribution towards the formulation of new semi-empirical correlations to be applied for the calculation of the flows normally found on a heat exchanger employed in the automotive industry. The proposed methodology will try to reach a general expression for the most common materials (copper, aluminium and stainless steel) and their regular range of surface finish in the nucleate boiling regime.

2. Background

2.1. Review of boiling heat transfer parameters

When trying to explain the different aspects that are known to have significance on boiling heat transfer, the common practice using semi-empirical models is to separate the influences into independent factors. Additionally, to improve the accuracy of the model, crossed dependences between some of these factors should be taken into account.

Probably since the first research on surface boiling, the main role that surface finishing and roughness play in nucleation characteristics has been assumed. For instance, in the early sixties, Berenson [14] noted the importance of including surface roughness in boiling analysis but focusing in surface finishing and in the morphology of the nucleation cavities. Moreover, assuming the fact that the surface finishing technique does not essentially affect other properties of the material such as ductility, malleability or hardness, thermal properties of the material have an apparent role in the transient conduction process near a nucleation site.

Marto and Rohsenow in 1965 [15] analysed previous studies of several authors and emphasised at least three effects concerning the surface that have a considerable effect on bubble nucleation: surface roughness, surface material and wetting characteristics of the solid–liquid combination (in terms of oxidation layer, additives and impurities of the liquid and even in the state of stress of the system). In their research, they give, upon several simplifications, a stability model where the instability is caused by sudden deactivation of active nucleation sites. They developed their research studies for sodium, much more instable than ordinary fluids, and concluded that increasing the diffusivity of metal surface as well as effusivity leads to a higher stability. Also, the same effect is derived for the heat flux. They encountered that roughness affects the form of the boiling curve not only at the early stages of incipient boiling but also over the range of stable nucleation. Other effects such as ageing, hysteresis, chemical treatment of the surface, porous coating and of course pressure and fluid properties, also have a significant influence.

Tachibana et al. [16] have found that the critical heat flux point is strongly affected by the thickness of the heater using flat plates as test sections and suggest a new correlating parameter in terms of the heat capacity per unit of area (i.e.: $\delta_w \cdot \rho_w \cdot c_w$). They also noted oxidation and precipitation processes to have influence in CHF. According to Tachibana et al., at least a value of 0.88 mm is needed to be free of heat capacity effects in the case of stainless steel plates. Guglielmini and Nannei [17] report important effects on CHF below a threshold value for the wall thickness and give a correlation based on the wall's thermal effusivity for calculating the aforesaid value. Later Golobič and Bergles [18] reaffirm the